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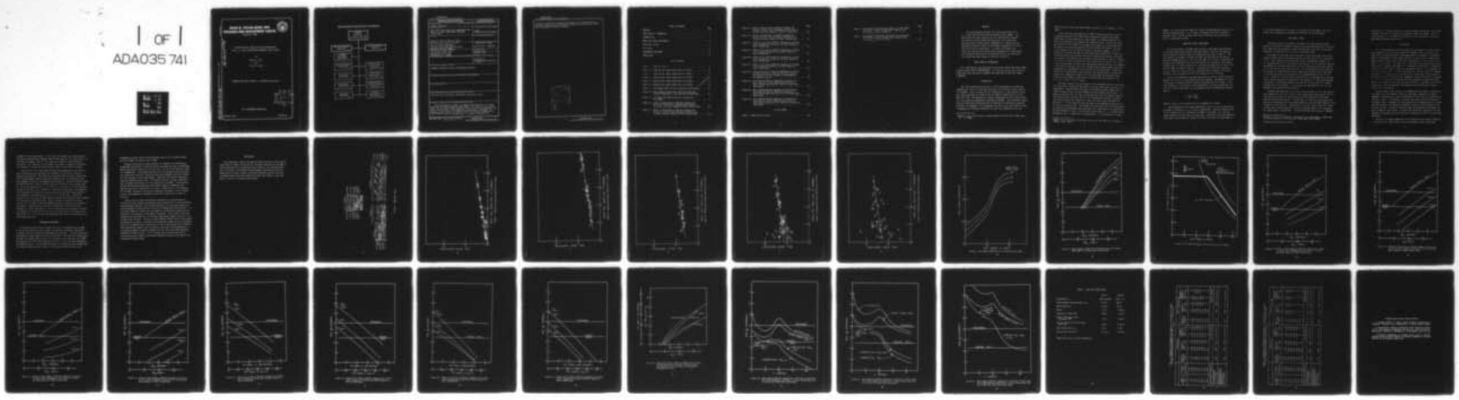

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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

PRELIMINARY ROLL STABILIZER SIZING PREDICTIONS
FOR A U.S. COAST GUARD MEDIUM ENDURANCE CUTTER (WMEC)

by

Edward W. Foley
and
Harry D. Jones

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

SHIP PERFORMANCE DEPARTMENT

November 1976 SPD-674-07

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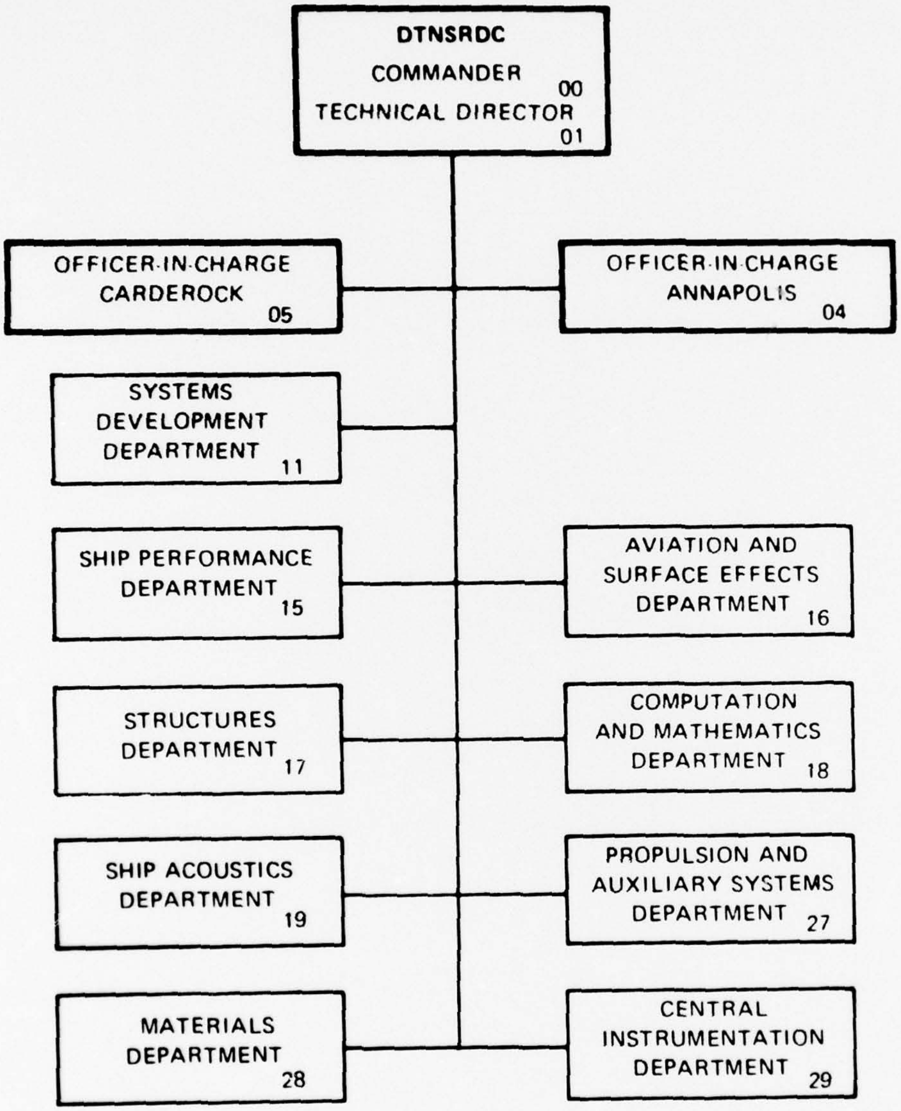

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This investigation provides roll motion predictions for a U. S. Coast Guard 270-foot Medium Endurance Cutter (WMEC). The predictions are used to assess the roll stabilization obtained with various sizes of bilge keels and active fin stabilizers. The predictions indicate that a reasonable roll response can be obtained with 9.67 m^2 (104 ft^2) bilge keels located aft of 2.32 m^2 (25 ft^2) active fin stabilizers. At higher ship speeds this

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stabilizer configuration should provide adequate roll stabilization for helicopter operations at all headings for most sea conditions with significant wave heights of around 3 m (9.8 ft).

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ABSTRACT

This investigation provides roll motion predictions for a U. S. Coast Guard 270-foot Medium Endurance Cutter (WMEC). The predictions are used to assess the roll stabilization obtained with various sizes of bilge keels and active fin stabilizers. The predictions indicate that a reasonable roll response can be obtained with 9.67 m^2 (104 ft^2) bilge keels located aft of 2.32 m^2 (25 ft^2) active fin stabilizers. At higher ship speeds this stabilizer configuration should provide adequate roll stabilization for helicopter operations at all headings for most sea conditions with significant wave heights of around 3 m (9.8 ft).

ADMINISTRATIVE INFORMATION

This investigation was authorized by the United States Coast Guard (USCG) funding document MIPR Z-70099-6-62370. The work was carried out at David W. Taylor Naval Ship R&D Center (DTNSRDC) and identified as Work Unit Number 1-1568-022.

INTRODUCTION

Roll motion predictions are given in this investigation to assess and recommend the size of a bilge keel and active fin stabilizer system required for the WMEC. Prior to making the roll predictions, it was necessary to conduct model experiments to measure the roll damping characteristics of the WMEC hull form. The measured roll damping characteristics were used as input to a roll prediction methodology developed at DTNSRDC. This procedure incorporates the prediction techniques given in Reference 1* modified to recognize nonlinear roll damping. The recommended size of the roll stabilization system is adequate for helicopter operations at worst ship heading for most sea

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*[1] Conolly, J.E., "Rolling and Its Stabilisation by Active Fins," RINA Trans., Vol. III (1969).

conditions with significant wave heights in the 3.0 - 3.5 m (9.8 m - 11.5 ft) range.

Roll predictions were made for the WMEC fitted with various sizes of bilge keels and active fin stabilizers at appropriate design ship speeds. Bilge keels are most effective at lower speeds, so a design speed of five knots was selected for the purpose of bilge keel sizing. On the other hand, active fins are more effective at higher ship speeds, so sizing predictions were done at the cruising speed of 15 knots as well as 12 knots. The ship is anticipated to be limited to 12 knots in the higher seaways. The roll predictions indicate the need for both bilge keels and active fin stabilizers. The 5-knot predictions indicate that even a maximum size (subject to design constraints) bilge keel may not provide the stabilization at lower ship speeds necessary to conduct undegraded helicopter operations for certain sea states in the desired range of significant wave heights with the ship at worst heading. A bilge keel of maximum length and tolerable width (from an added resistance standpoint) was selected for use in the fin sizing predictions. These predictions at 12 and 15 knots indicated that roll stabilization at higher ship speeds with a moderately sized fin will be sufficient for helicopter operations at worst heading in most seas with significant wave heights in the 3.0 to 3.5 m (9.8 - 11.5 ft) range.

To further evaluate the performance of the selected bilge keels and active fin stabilizers, predictions were made for various conditions over the entire speed range. The additional conditions investigated included comparisons of inactive versus active fins and nonadaptive versus adaptive controllers. An adaptive controller has its logic so designed that the fin system can adapt to lower wave heights such that the fins still operate with optimum fin angles thus providing more roll reduction in lower sea states than a nonadaptive controller. A final evaluation was also made of the assumed sea spectra used for the sizing predictions. The seaways for these predictions were constructed by assuming a Bretschneider spectral shape with a model period corresponding to the most probable to occur in the Northern North Atlantic, i.e., between 40 and 60 degrees north, as determined from Reference 2. As an evaluation of these

[2] Hogben, N. and F.E. Lumb, "Ocean Wave Statistics," Her Majesty's Stationery Office, London (1967).

seaways, roll predictions were made for a family of Bretschneider spectra with a range of modal periods. In all cases, the seaways were short crested by assuming a cosine square spreading function of the wave energy $\pm$ 90 degrees from the predominant heading.

MODEL ROLL DECAY EXPERIMENTS

For the experiments, the WMEC model (without bilge keels) was ballasted to the load conditions provided by the Coast Guard. The specified load conditions along with the principal ship dimensions are given in Table 1. The roll gyradius is unknown, therefore the model was ballasted to the correct waterline and $\overline{GM}$ value only. The resulting model roll period was measured and assumed to be representative of the ship natural roll period for the purpose of making the roll motion predictions. The body plan and profile lines of the 270-foot WMEC are shown in Figure 1. The model was fitted with a steering servo, DC motor for propulsion and a stabilized gyro to measure roll angles. The model was free-running with no rigid constraints on its motions.

During the experiments, the model was heeled to various initial angles at speeds of 0, 5, 10, 15, and 20 knots and then released. The damped roll oscillations were recorded on magnetic tape and displayed on a strip chart. From these damped roll oscillations, the nondimensional roll decay coefficient for the ship without bilge keels, n_o, was computed using the mathematical approximation

$$n_o = \frac{1}{2\pi} \ell n \frac{\phi_i}{\phi_{i+1}}$$

where ϕ_i and ϕ_{i+1} are successive port to starboard roll angles.

The nondimensional roll decay coefficients for 0, 5, 10, 15, and 20 knots are shown in Figures 2, 3, 4, 5, and 6, respectively. The data indicates that for all speeds, the roll response of the WMEC is nonlinear, i.e., the roll decay coefficient varies with roll amplitude. The faired lines from these data plots were cross plotted as is shown in Figure 7 for mean roll amplitudes of

5, 10, and 15 degrees with n_o given as a function of ship speed. This plot allows one to approximate the damping coefficient for any ship speed.

BILGE KEEL SIZING

Since bilge keels are primarily low speed roll stabilization devices, efforts to determine a suitable bilge keel size were concentrated on five knots. Roll predictions were made for a range of bilge keel sizes and a selection of bilge keel was made for use in the fin sizing predictions.

The range of bilge keel sizes consisted of three bilge keels each with a length of 15.9 m (52 ft) and spans of 0.30 m (1 ft), 0.61 m (2 ft), and 0.91 m (3 ft). The bilge keels were designated as BK1, BK2 and BK3, respectively, for convenience and are so indicated on the figures. A fin stabilizer location was selected by the Coast Guard prior to this investigation at a point 29.9 m (98 ft) aft of the forward perpendicular. With bilge keels and fins being the anticipated roll stabilization system, proper design practice will not allow for significant amounts of bilge keel to be located forward of this fin location. Therefore, the bilge keel length specified is the approximate maximum length that can be properly located aft of an active fin. This fin/bilge keel orientation is unfortunate because bilge keel aft of an active fin in effect degrades the fin performance. In this case, the degradation on fin lift was computed to be approximately 30 percent.

Unstabilized predictions, at 5 knots, show the need for roll stabilization when compared with the roll criteria. The unstabilized predictions (no fins or bilge keels) are shown in Figure 8 along with the predicted stabilization obtained with BK1, BK2 and BK3. The personnel criterion was interpreted from data given in Reference 3 on crew effectiveness on the USS GLOVER (reported roll frequency of 0.67 rad/sec). The personnel criterion line on Figure 8 is meant to imply that crew performance* is likely to degrade rapidly with increasing roll angles above 4 degrees RMS. The Naval Ship Engineering Center's (NAVSEC)

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[3]Warhurst, F. and A.L. Cerasani, "Evaluation of the Performance of Human Operations as a Function of Ship Motion," NSRDC Report 2828 (1969).

*Excluding any seasickness effects.

criterion for helicopter operations is also indicated on Figure 8. This figure indicates the need for maximum stabilization at lower ship speeds. With resistance aspects in mind, BK2 was selected for use during the fin sizing and performance assessment predictions.

FIN SIZING

Fin sizing computations were performed for ship speeds of 12 and 15 knots for a range of fin sizes with an assumed fin geometric aspect ratio of 1.0, taper ratio of 0.45 and quarter chord sweep angle of 11 degrees. Although 15 knots is the assumed cruising speed, the ship is likely to be limited by the seas to around 12 knots when significant wave heights are in the 3.0 to 3.5 m (9.8 - 11.5 ft) range. Two types of fin controllers were considered for these predictions; nonadaptive and adaptive. A nonadaptive controller is assumed to be a controller designed to take full advantage of the fin limiting angles for a design high sea state. In lower sea states this type of controller responds with smaller fin angles due to the smaller roll angle input to the controller. For the purposes of simulating this nonadaptive type of controller, a reduction in limiting fin angles of 10 percent per metre decrease of significant wave height was assumed for seas less than 5.0 m (16.4 ft). The adaptive controller, on the other hand, was assumed to be operating with the maximum fin angle limits in all sea states.

Several factors that reduce fin performance are not properly accounted for by present "state-of-the-art" prediction techniques, therefore, an overall degradation was applied to the lift characteristics of the fin to produce more realistic results. These factors include: losses due to the fin operating in a boundary layer, allowances for the assumption of an "opposed control" system, sway and yaw coupling effects and mechanical losses to be anticipated in the fin-servo system. An overall reduction factor of 20 percent was assumed as a best estimate of these losses. An additional 30 percent reduction in fin performance was assumed due to the bilge keel located aft of the fin as previously mentioned.

The fin limit angles chosen for this investigation are shown in Figure 9. In the prediction scheme, these limits are assumed to have a 10 percent

probability of being exceeded. At the lower ship speeds, the limits were determined by maintaining a 2-degree safety factor below the fin stall angle. At the high ship speeds, the fin limit angles are reduced to avoid excessive cavitation. The reduction in limit angles with speed is guided by the cavitation inception line and the stock design strength relationship with speed.

Using the fin limit angles and the described degradations, the 12 and 15 knot sizing predictions were made for the WMEC with the results plotted in Figures 10 through 18. The predictions were again made for short crested seas with a Bretschneider spectral shape and a modal period corresponding to the most probable to occur in the Northern North Atlantic. Three fin planform areas of 1.86 m^2 (20 ft^2), 2.79 m^2 (30 ft^2) and 3.72 m^2 (40 ft^2) were examined with the results designated as Fin 1, Fin 2 and Fin 3, respectively, on the figures. Figures 10 through 13 give the RMS roll response for bilge keels only (BK2) and for bilge keels with active fins as a function of significant wave height for both nonadaptive and adaptive controllers at 12 and 15 knots. Figures 14 through 17 are cross plots of this data to show the relationship of roll response with increasing fin planform area. Figure 18 shows the required fin area necessary for the WMEC to meet the NAVSEC helicopter criterion as a function of wave height. Based upon this figure, a fin area of 2.32 m^2 (25 ft^2) was selected for further examination. This fin area meets the helicopter criterion at 12 knots with either type of controller with significant wave heights up to 3.25 m (10.7 ft). This fin area was designated FIN* and will be referred to in the following section.

PERFORMANCE ASSESSMENT

This section gives further insight into the roll performance of the WMEC by (a) giving predictions across speed, (b) looking at different operational situations, and (c) evaluating the assumed sea conditions. The roll predictions were made for speeds ranging from zero to 20 knots. The conditions investigated included (a) unstabilized (no fins or bilge keels); (b) bilge keels only (BK2); (c) inactive fins (FIN*) and bilge keels; (d) active fins with both nonadaptive and adaptive control. The assumed sea spectra, with modal periods corresponding to the most probable period to occur in the Northern North Atlantic, were

evaluated by using a family of Bretschneider spectra with a range of modal periods to make roll predictions for WMEC.

Figures 19 through 21 present the RMS roll response for the different operational situations as a function of the ship speed for short crested waves having significant heights of 2.5 m (8.2 ft), 3.5 m (11.5 ft) and 5.5 m (18.0 ft), respectively. The unstabilized (no fins or bilge keels) and bilge keels only predictions show that 5 knots may have given somewhat optimistic results for the bilge keel sizing investigation. Both zero and 10-knot predictions show more response than 5 knots. This should serve as a further indication that low speed stabilization may be a problem with the WMEC. Figures 19 and 20 show the predicted differences anticipated between a nonadaptive and adaptive controller (indicated as N.A. and A., respectively, on the figures) for the WMEC. Because of the design assumptions discussed in the Fin Sizing section, the nonadaptive and adaptive controller results are the same in Figure 21.

Tables 2 and 3 present performance assessments for selected cases to evaluate the wave frequency assumptions used to simplify the sizing predictions. The assumptions made were that the modal periods of the sea spectra were the maximum probability modal periods occurring in the Northern North Atlantic. In the tables, WMEC roll predictions are shown for various modal periods and the probability of exceeding 5 and 8 degrees tabulated. These probabilities were combined with the probability of the given modal period seaway occurring in the Northern North Atlantic. The sum of these combined probabilities, given towards the bottom of the tables, represents the conditional probabilities of exceeding either 5 or 8 degrees over a long period of time in the Northern North Atlantic. These conditional probabilities are smaller than either Pierson-Moskowitz or the maximum probability spectra probabilities for the various WMEC operating conditions of Tables 2 and 3. This indicates that the bilge keel and fin sizing predictions, based on the maximum probability modal period spectra, are conservative design values.

CONCLUSIONS

The predictions indicate the need for both bilge keels and active fin stabilizers to reduce roll motion for helicopter operations on the WMEC in seas representative of the Northern North Atlantic. The selected bilge keel and fin pair sizes should provide adequate stabilization for ship speeds above 12 knots; however, helicopter operations may be restricted to headings other than worst heading for lower ship speeds in seas with about 3 m (9.8 ft) significant wave height.

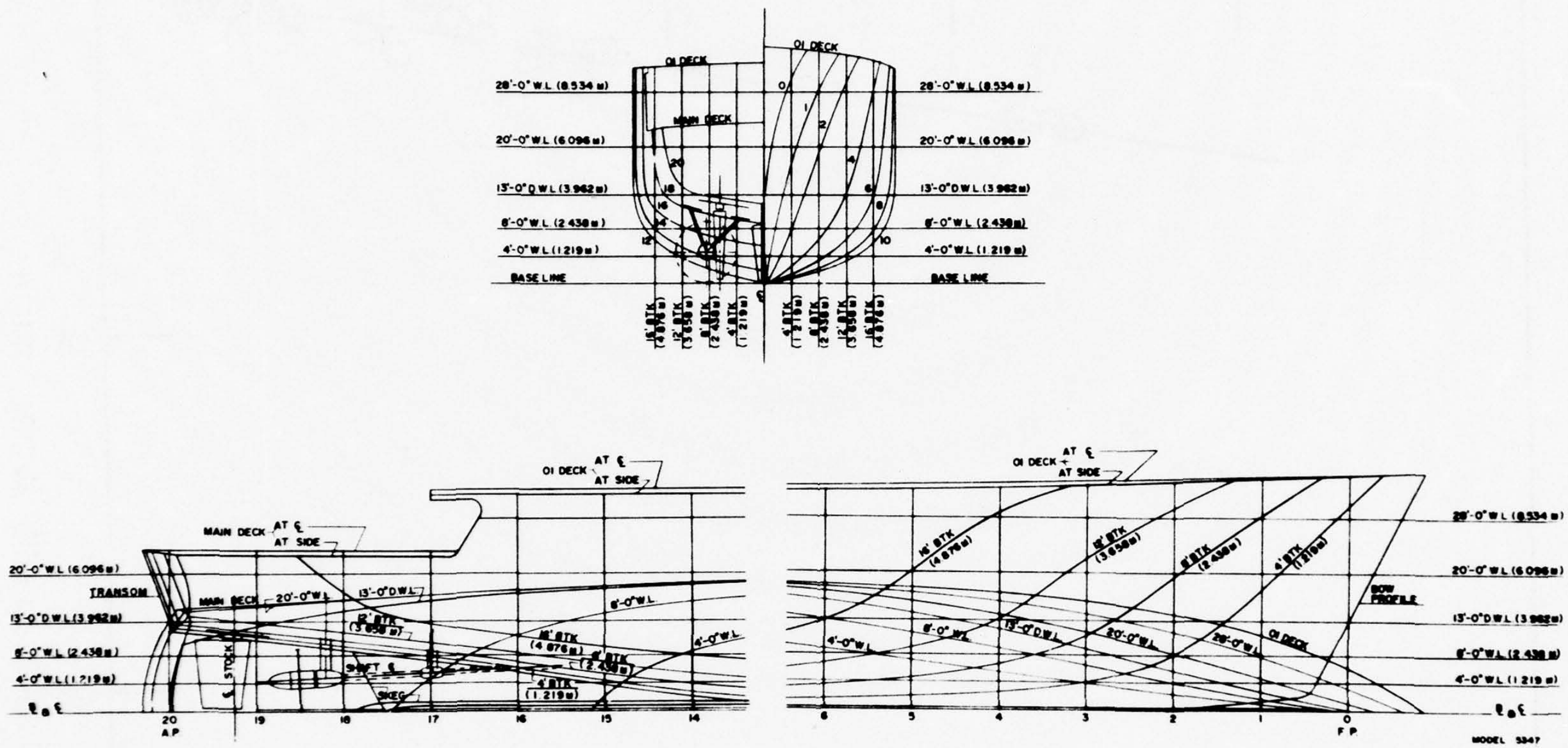

Figure 1 - WMEC Hull Plan

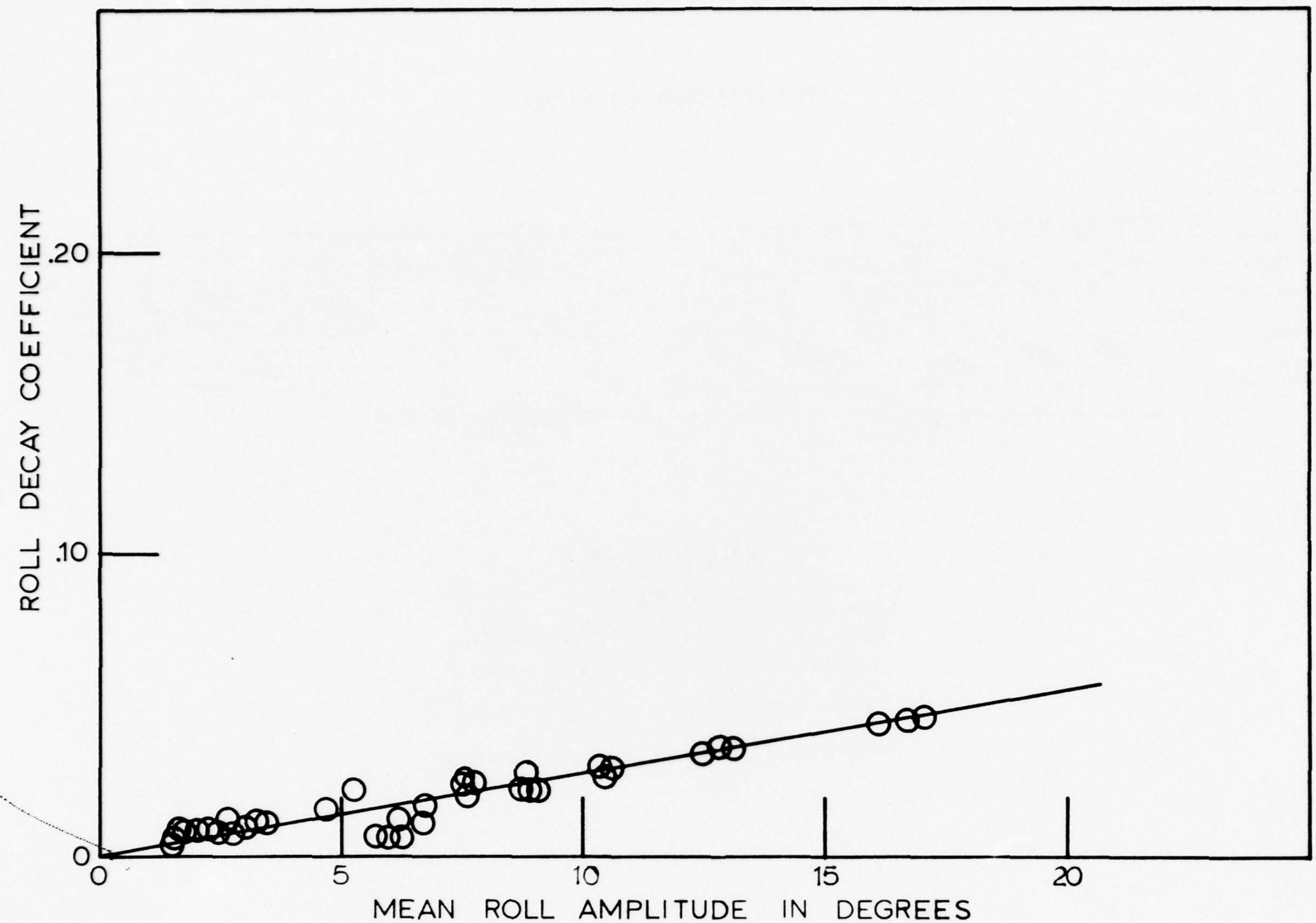

Figure 2 - Measured Roll Decay Coefficient at 0 Knots

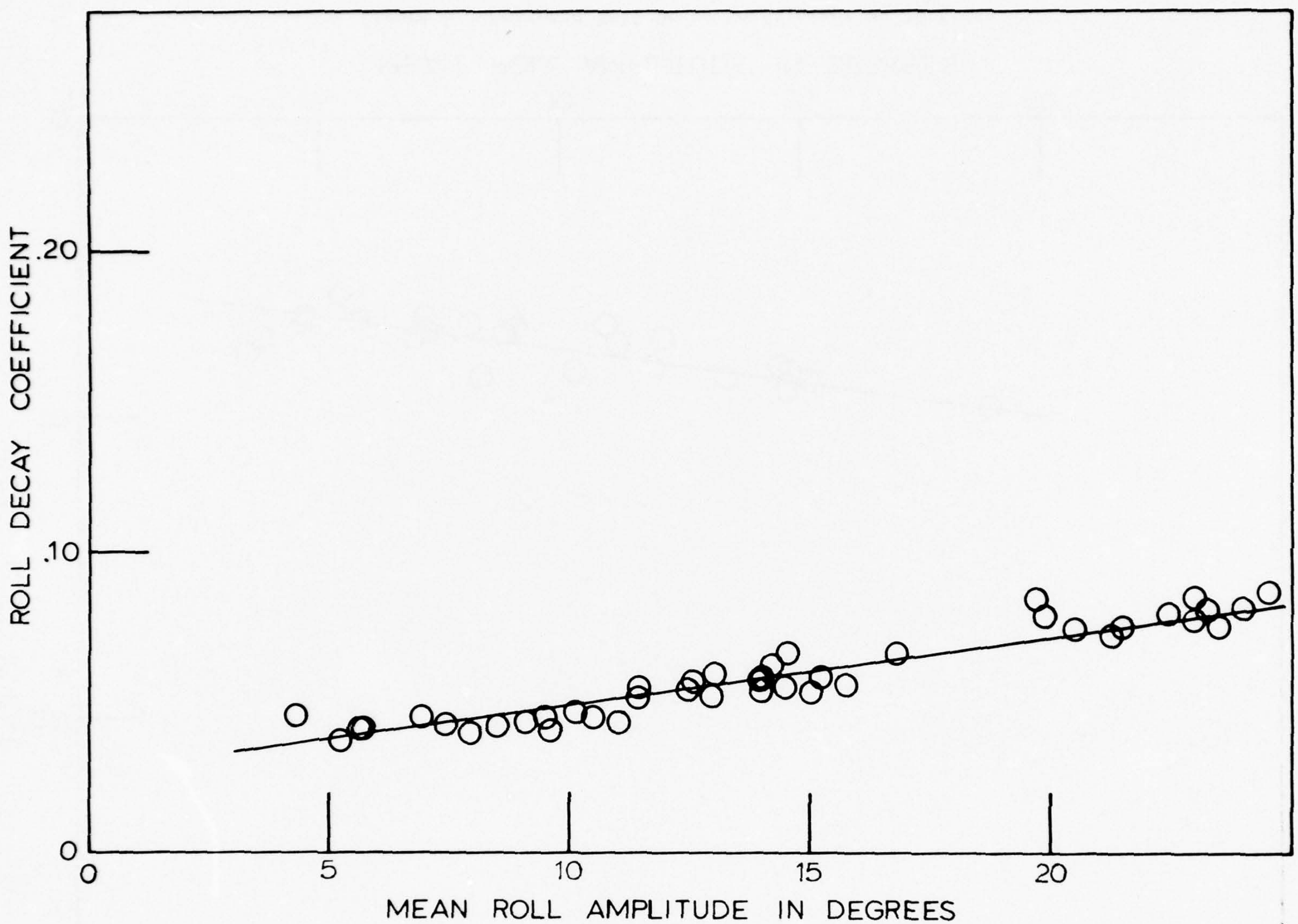

Figure 3 - Measured Roll Decay Coefficient at 5 Knots

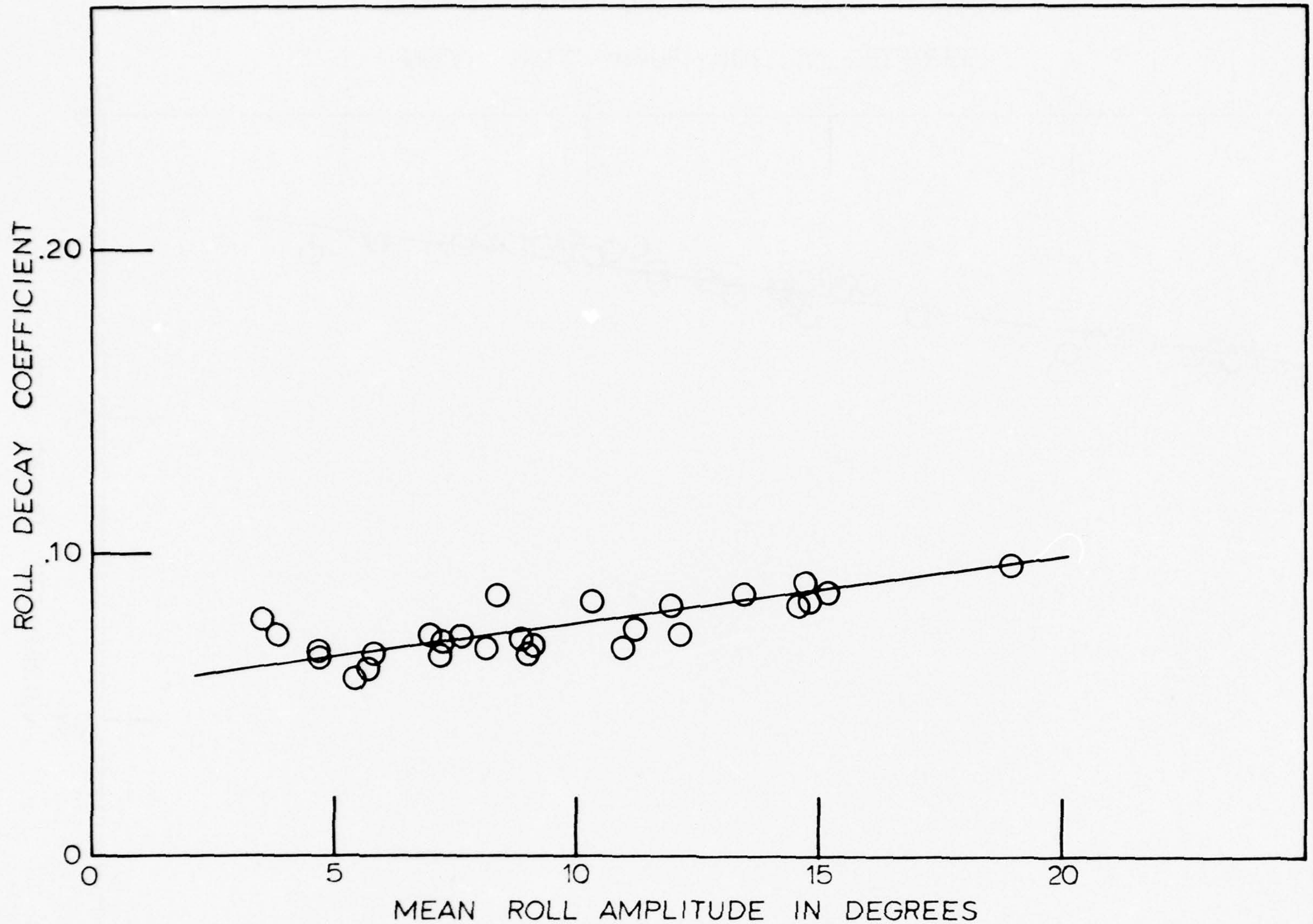

Figure 4 - Measured Roll Decay Coefficient at 10 Knots

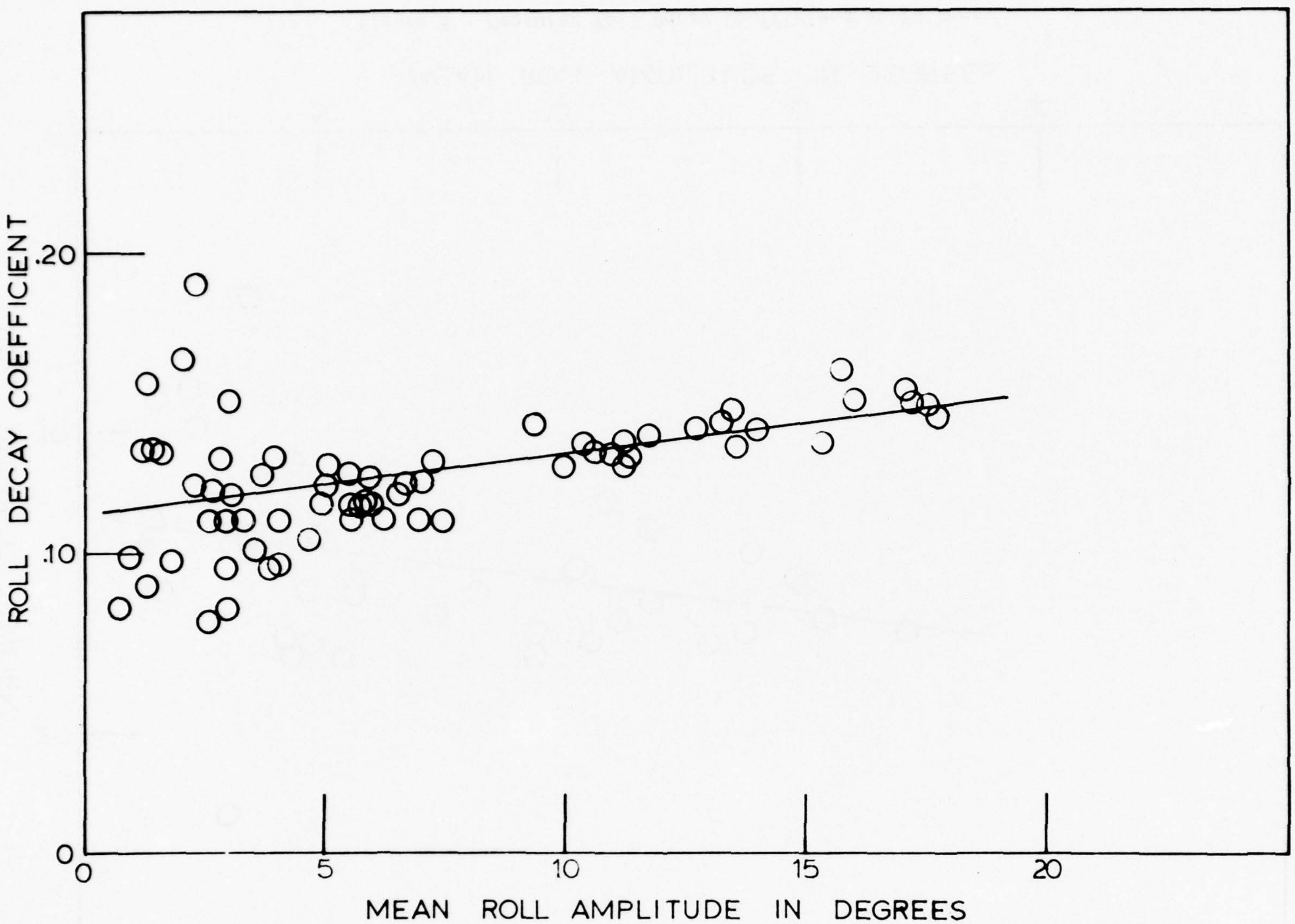

Figure 5 - Measured Roll Decay Coefficient at 15 Knots

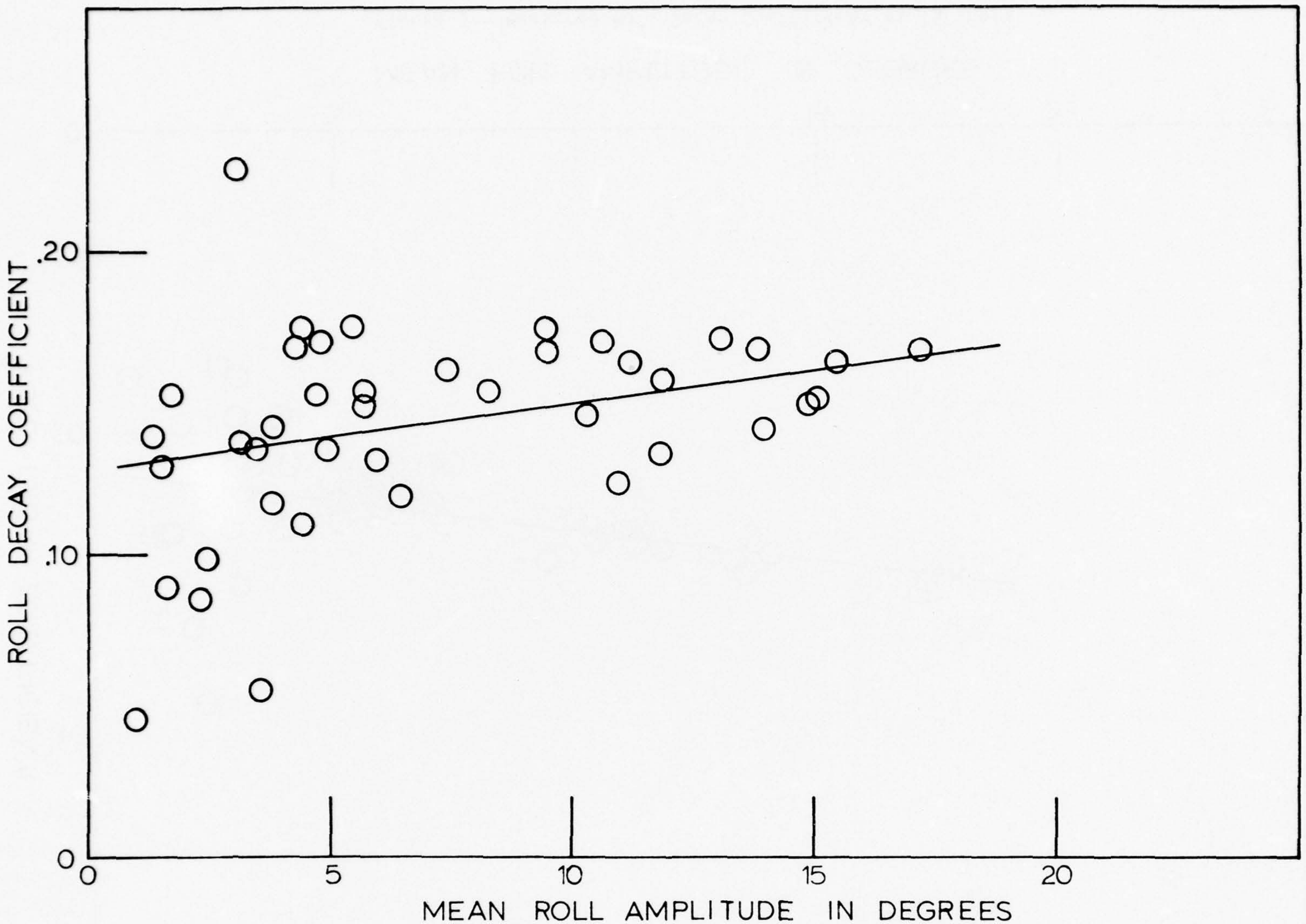

Figure 6 - Measured Roll Decay Coefficient at 20 Knots

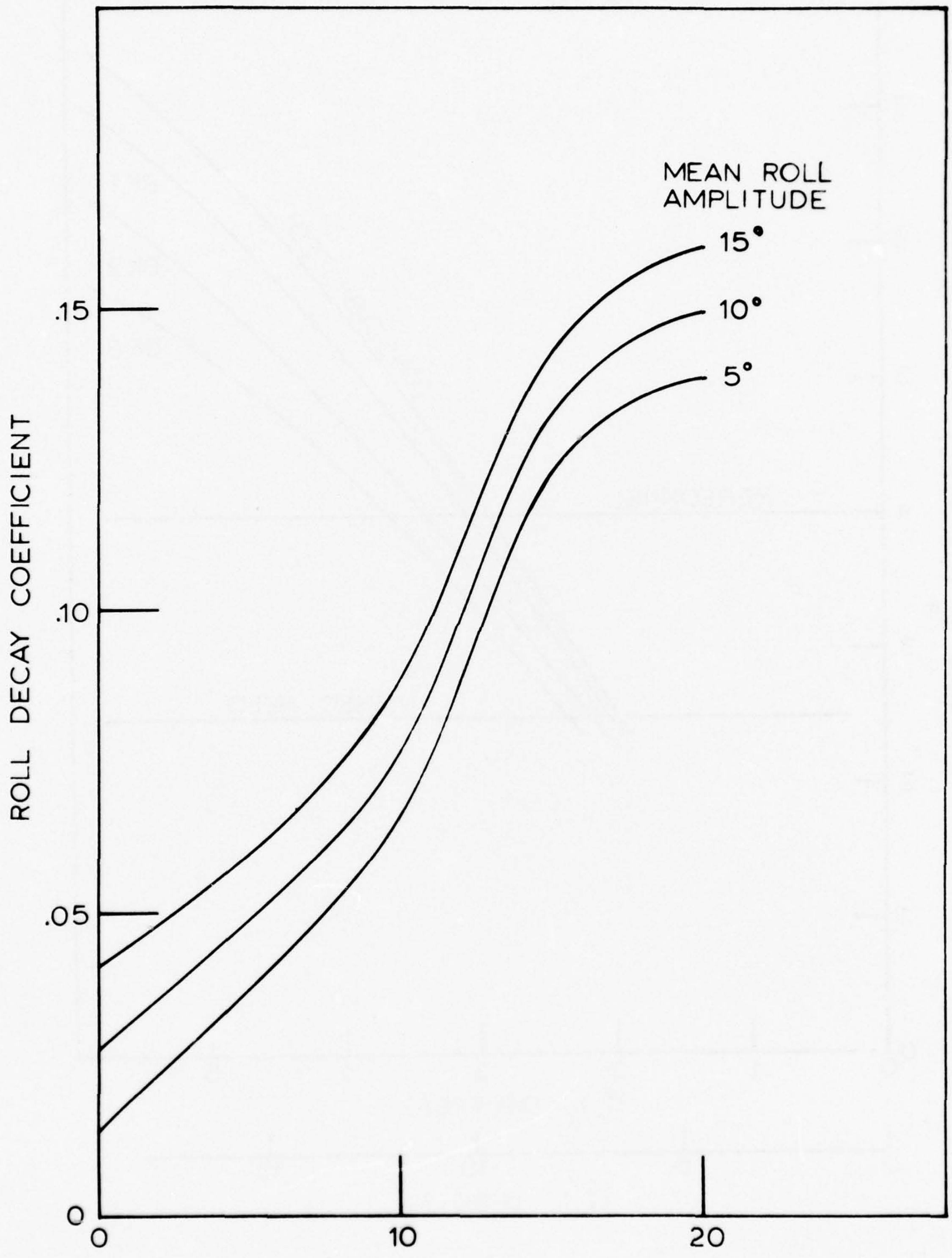

Figure 7 - Roll Decay Coefficient as a Function of Ship Speed

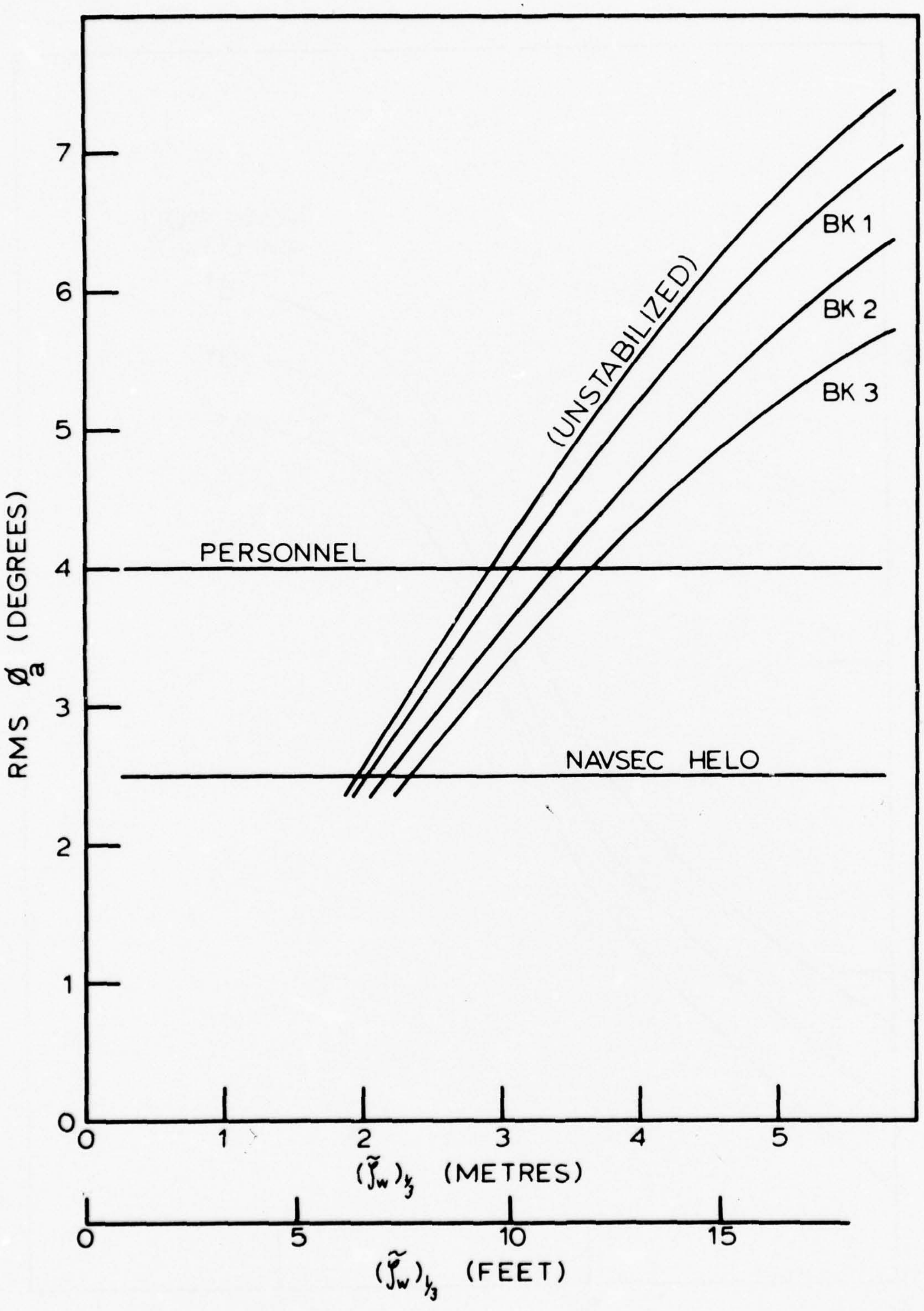

Figure 8 - Worst Heading 5-Knot Roll Predictions With and Without Bilge Keels in Various Short Crested Seas

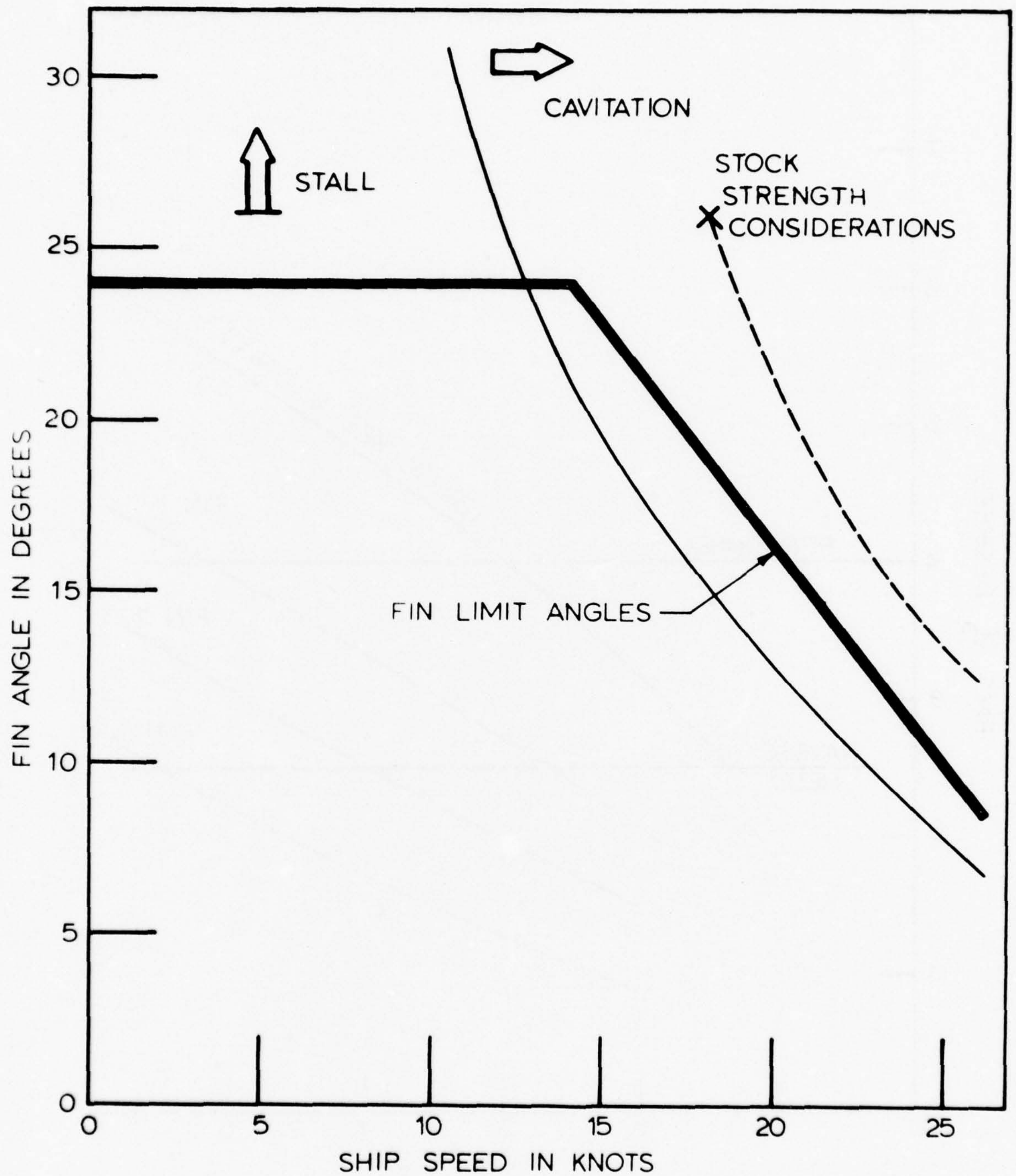

Figure 9 - Fin Stabilizer Angle Limits as a Function of Ship Speed

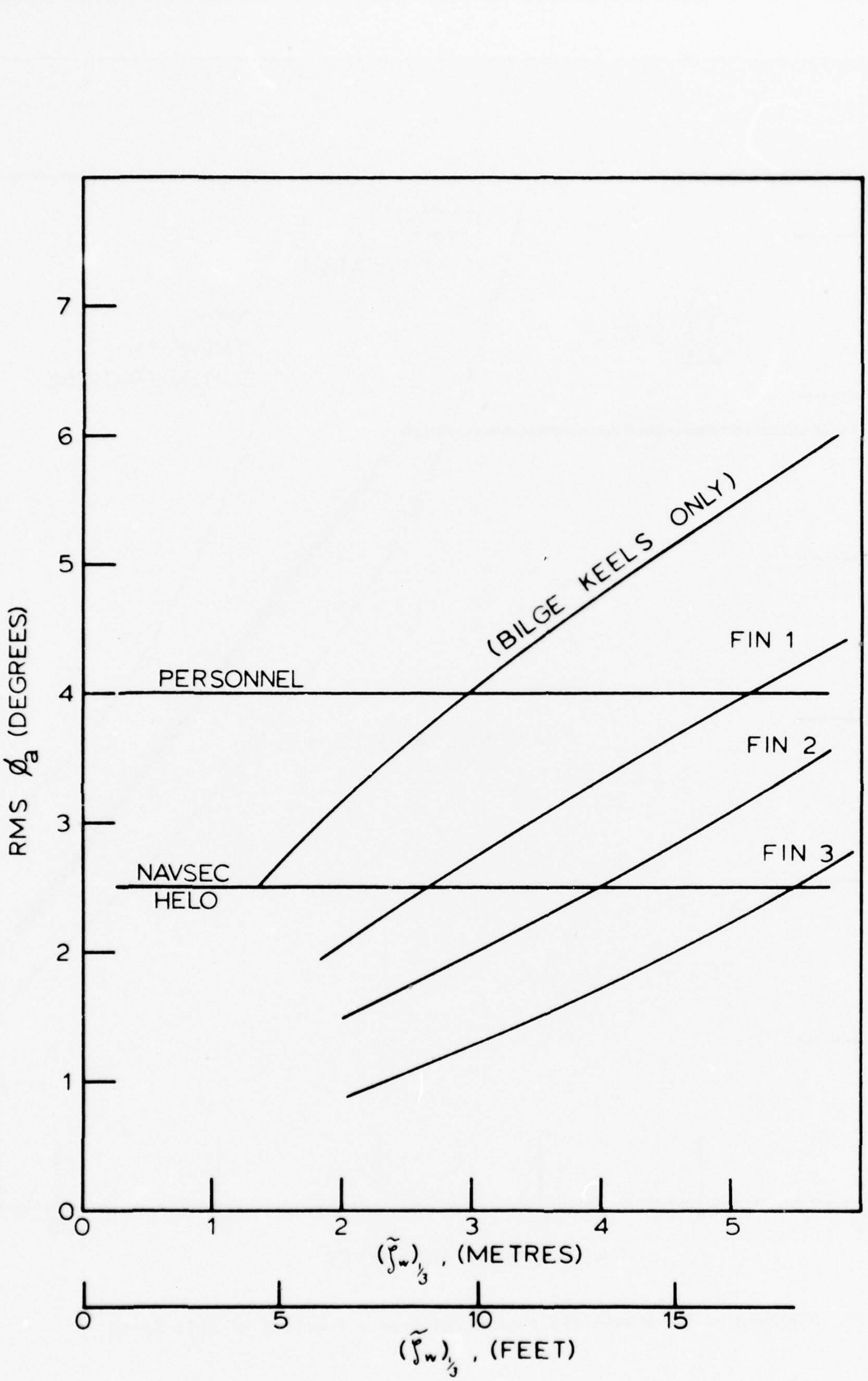

Figure 10 - Effect of Wave Height on RMS Roll Response for Various Fin Pairs with a Nonadaptive Controller at 12 Knots and Worst Heading in Short Crested Seas

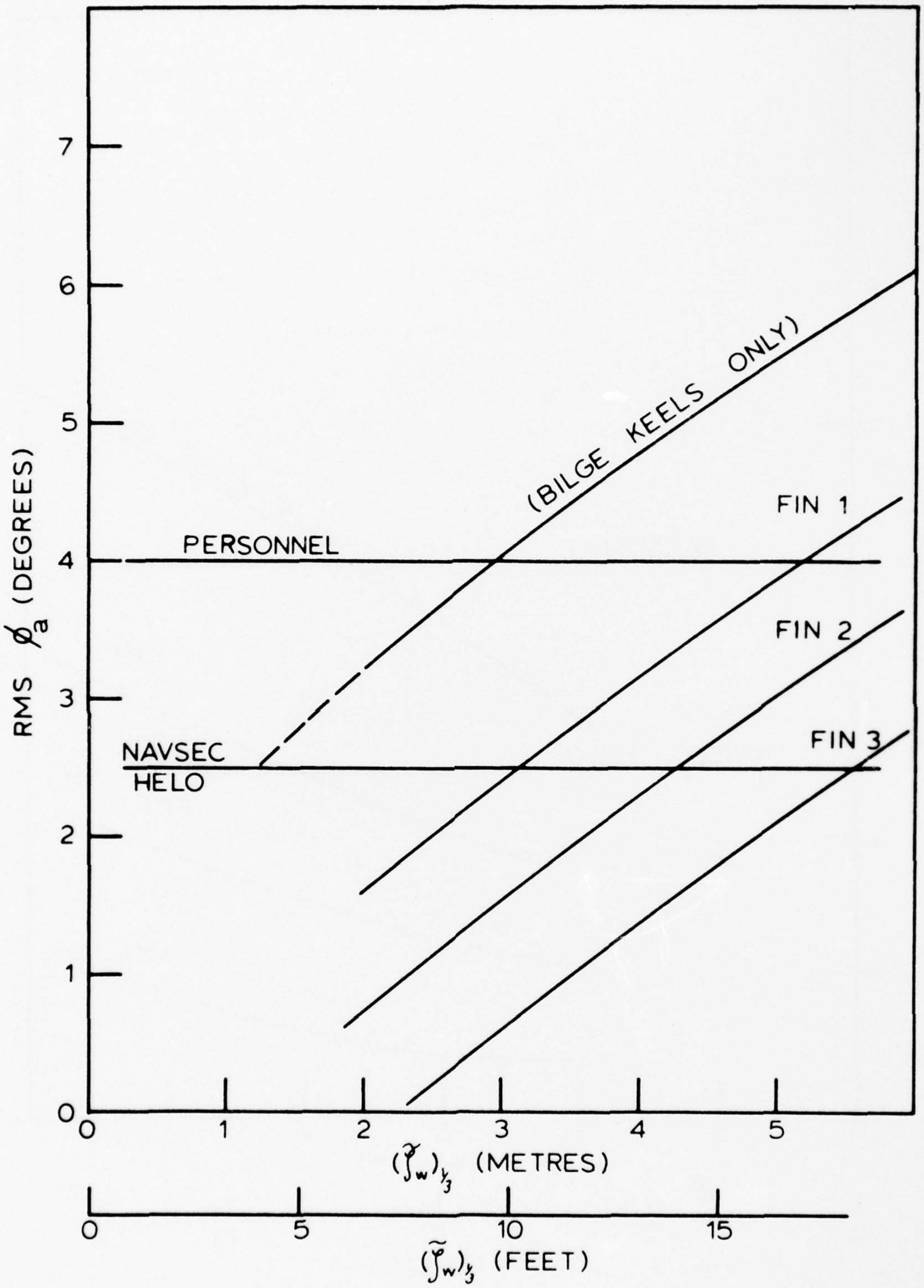

Figure 11 - Effect of Wave Height on RMS Roll Response for Various Fin Pairs with an Adaptive Controller at 12 Knots and Worst Heading in Short Crested Seas

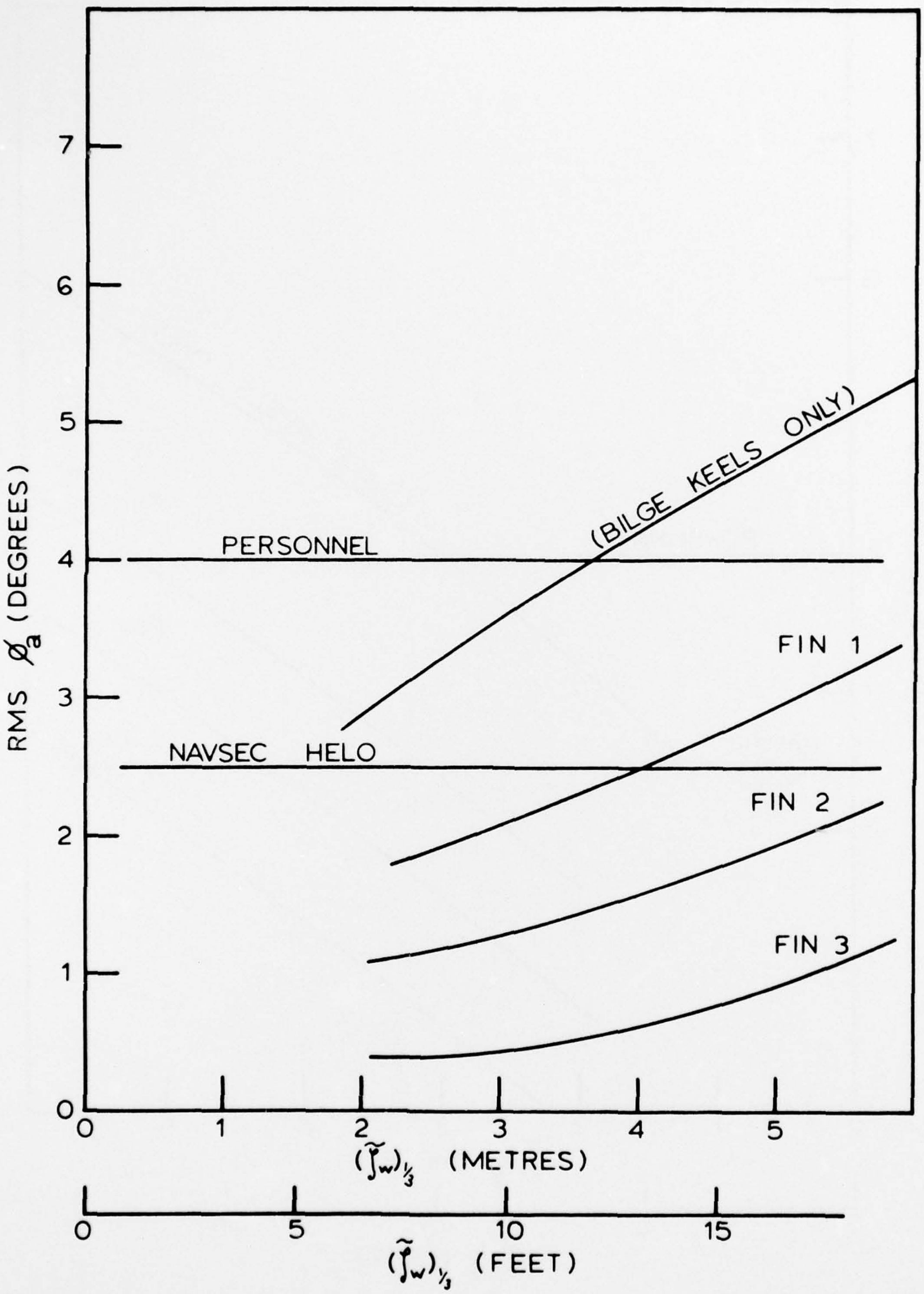

Figure 12 - Effect of Wave Height on RMS Roll Response for Various Fin Pairs with a Nonadaptive Controller at 15 Knots and Worst Heading in Short Crested Seas

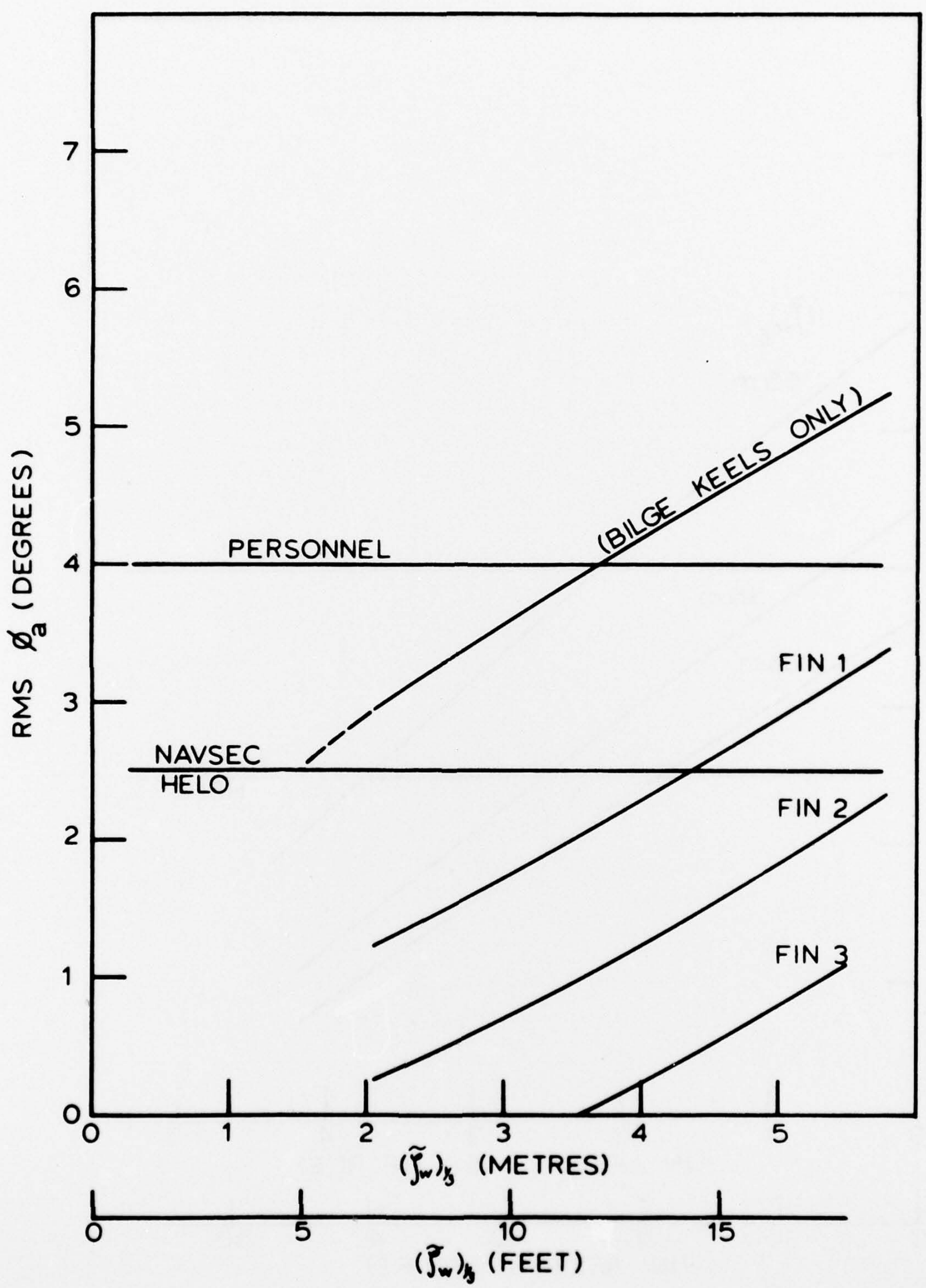

Figure 13 - Effect of Wave Height on RMS Roll Response for Various Fin Pairs with an Adaptive Controller at 15 Knots and Worst Heading in Short Crested Seas

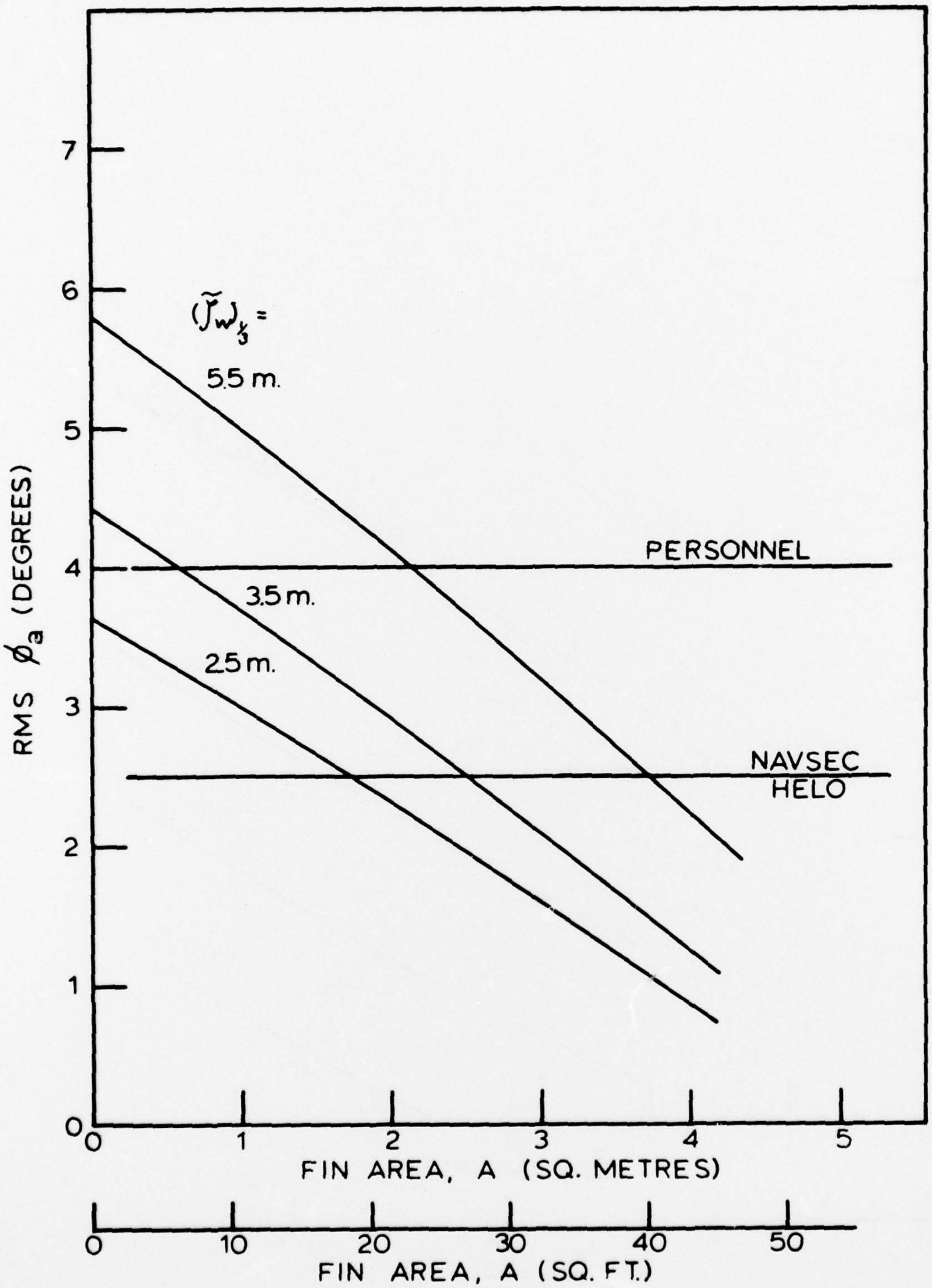

Figure 14 - Effect of Fin Area on RMS Roll Response at 12 Knots with a Nonadaptive Controller and Worst Heading in Short Crested Seas

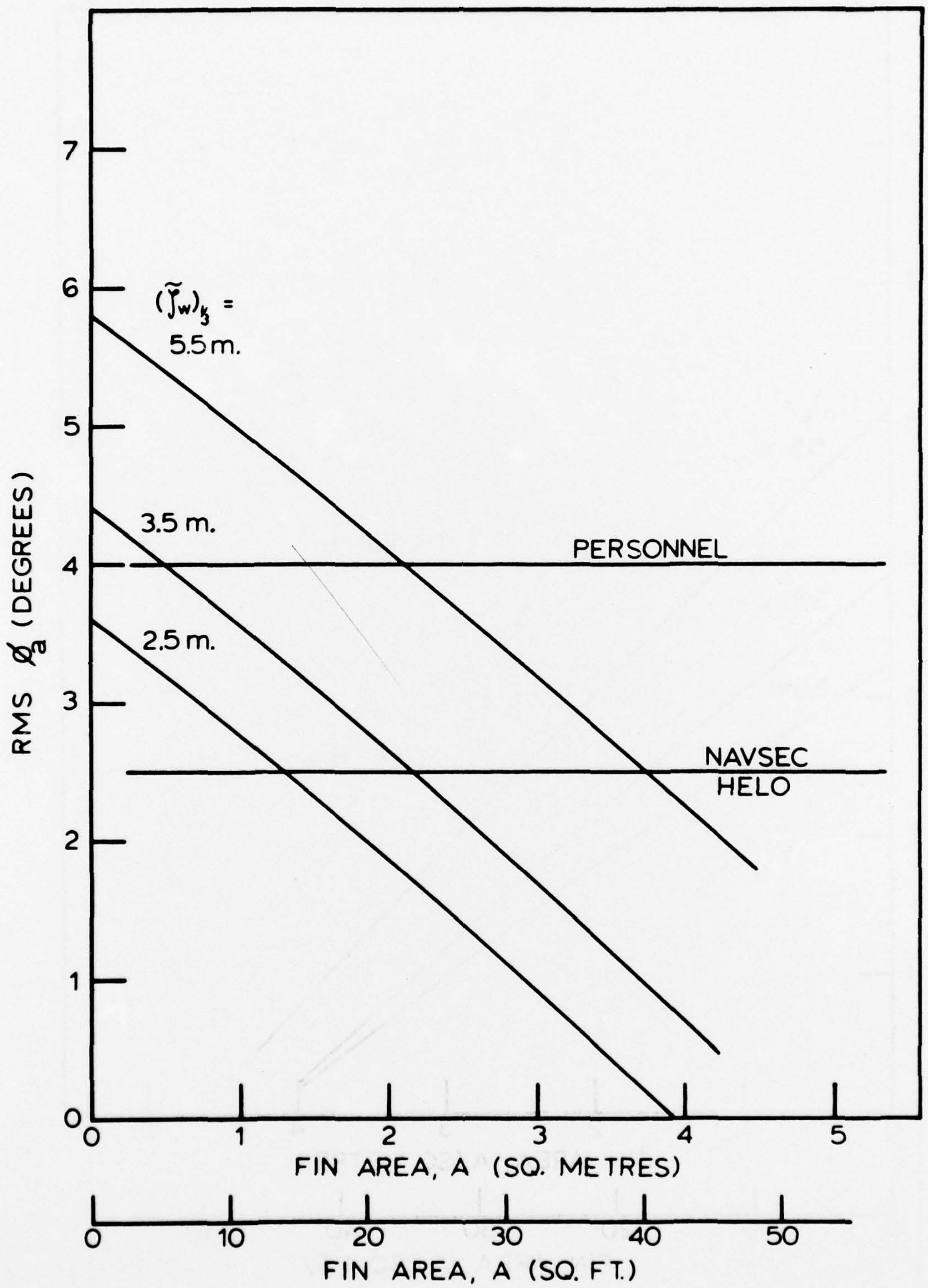

Figure 15 - Effect of Fin Area on RMS Roll Response at 12 Knots with an Adaptive Controller and Worst Heading in Short Crested Seas

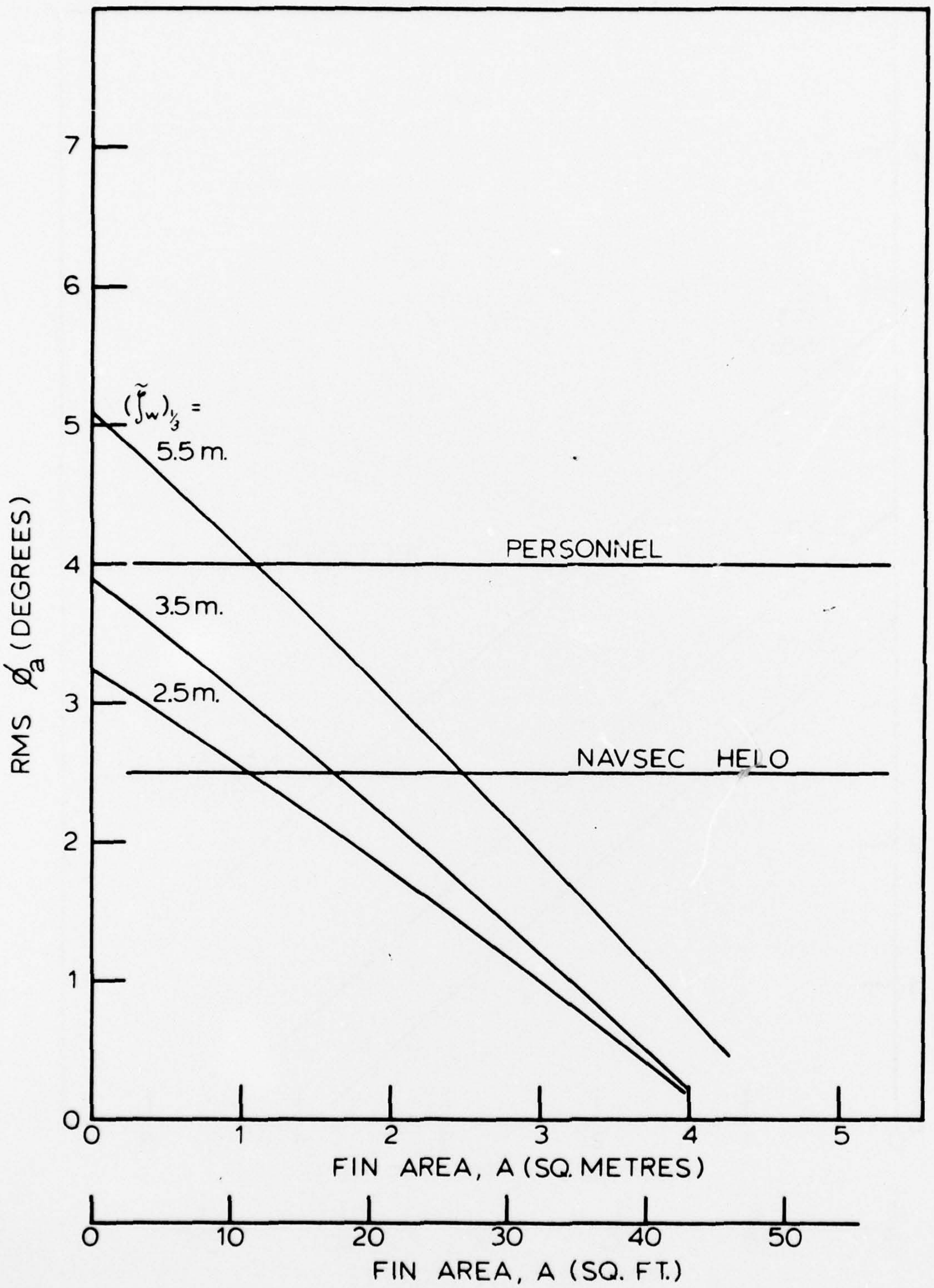

Figure 16 - Effect of Fin Area on RMS Roll Response at 15 Knots with a Nonadaptive Controller and Worst Heading in Short Crested Seas

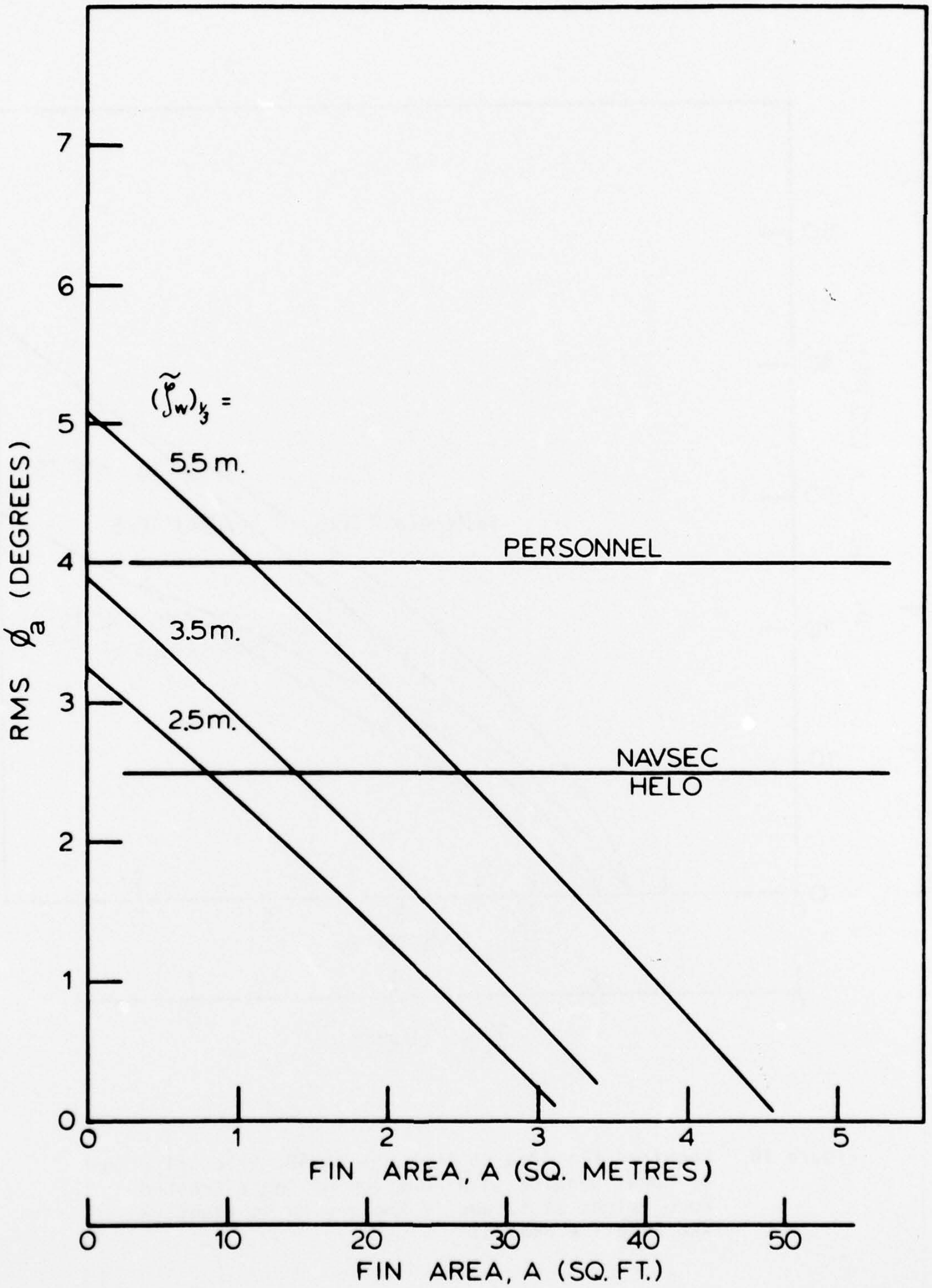

Figure 17 - Effect of Fin Area on RMS Roll Response at 15 Knots with an Adaptive Controller and Worst Heading in Short Crested Seas

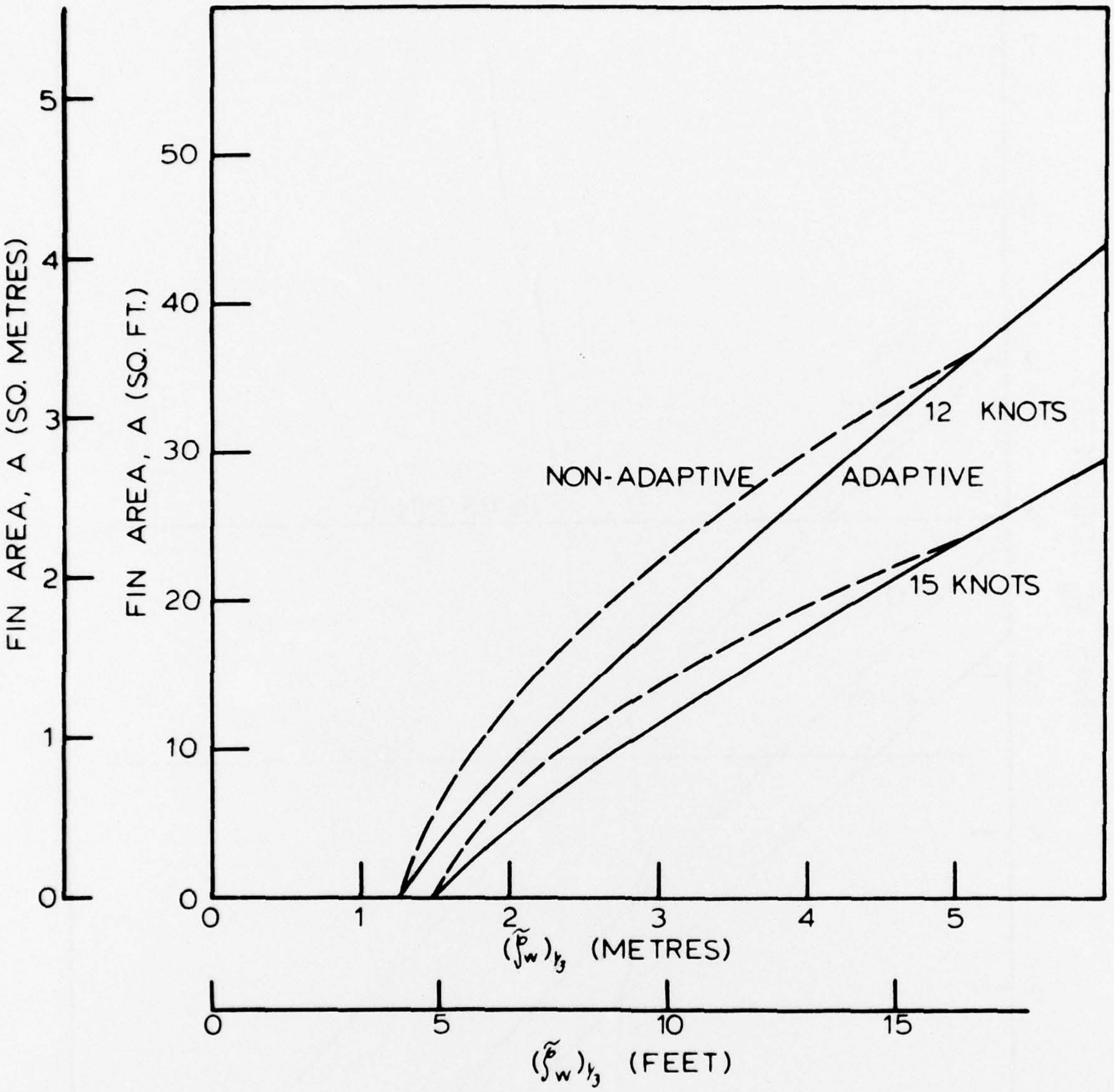

Figure 18 - Required Fin Area to Meet the NAVSEC Helo Criterion at Worst Heading as a Function of Short Crested Wave Height at 12 and 15 Knots with Nonadaptive and Adaptive Control

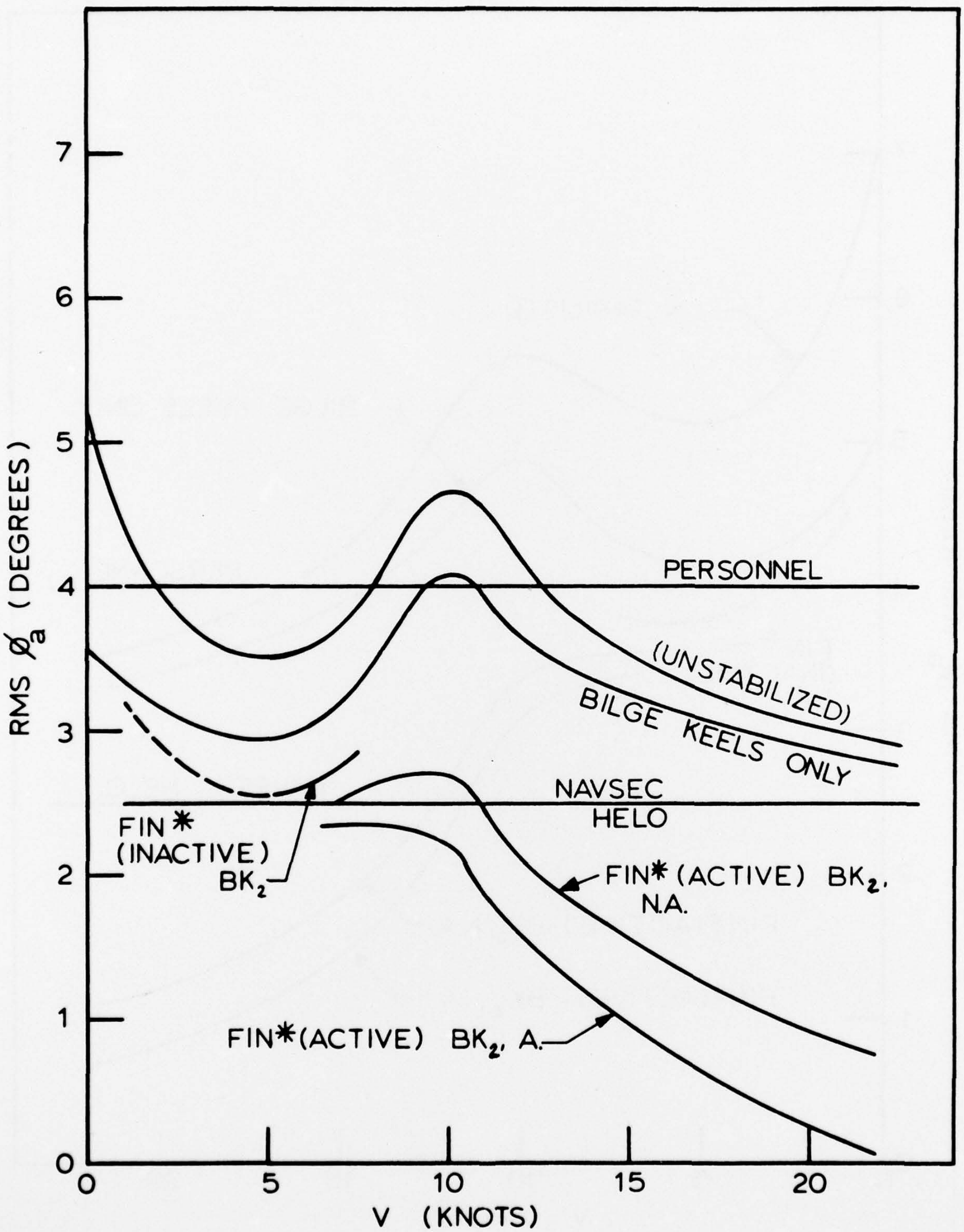

Figure 19 - Worst Heading RMS Roll Response as a Function of Ship Speed for Various Operating Conditions in Short Crested Seas with 2.5 m (8.2 ft) Significant Wave Height

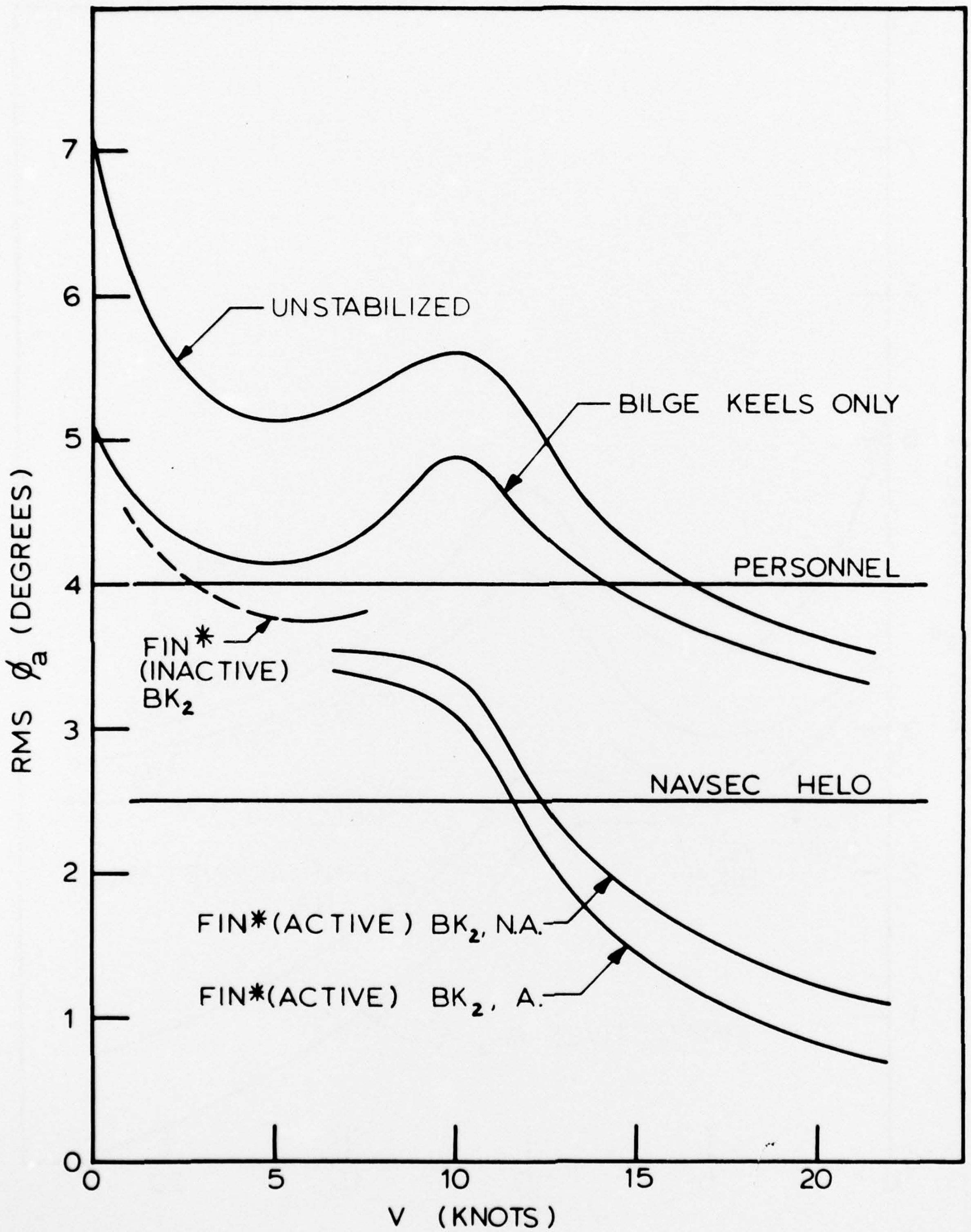

Figure 20 - Worst Heading RMS Roll Response as a Function of Ship Speed for Various Operating Conditions in Short Crested Seas with 3.5 m (11.5 ft) Significant Wave Height

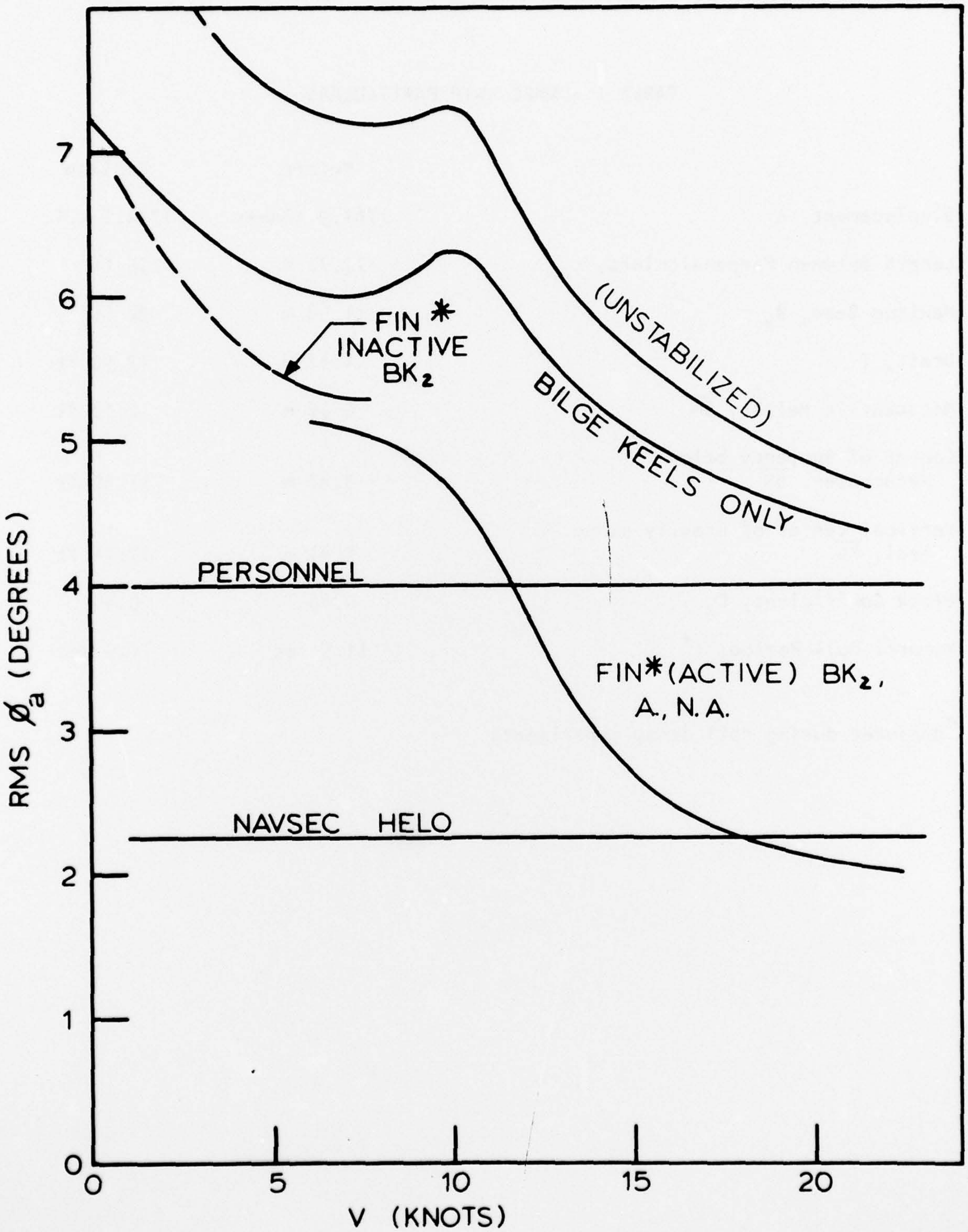

Figure 21 - Worst Heading RMS Roll Response as a Function of Ship Speed for Various Operating Conditions in Short Crested Seas with 5.5 m (18.0 ft) Significant Wave Height

TABLE 1 - WMEC SHIP PARTICULARS

	Metric	English
Displacement, Δ	1761.9 tonnes	1734.1 L.T.
Length Between Perpendiculars, L_{PP}	77.72 m	255 ft
Maximum Beam, B_X	11.58 m	38 ft
Draft, T	4.12 m	13.50 ft
Metacentric Height, $\overline{GM}$	0.66 m	2.18 ft
Center of Buoyancy below Metacenter, $\overline{BM}$	3.47 m	11.40 ft
Vertical Center of Gravity above Keel, $\overline{KG}$	5.41 m	17.74 ft
Block Coefficient, C_B	0.46	0.46
Natural Roll Period, T^*	11.5 sec	11.5 sec

*Measured during roll decay experiments.

TABLE 2 - HYDRODYNAMIC PERFORMANCE ASSESSMENT AT A SHIP SPEED OF 5 KNOTS IN SHORT CRESTED, WORST HEADING SEAS WITH $(\tilde{\zeta}_w)_{1/3}$ = 3.5 M (11.5 FT)

		Unstabilized					Fin* (Inactive) BK_2				
Modal Period, T_o sec	Frequency of Occurrence	RMS Roll Amplitude deg	Probability that ϕ_a > $\pm 5°$	Probability that ϕ_a > $\pm 8°$	Combined Probability that ϕ_a > $\pm 5°$	Combined Probability that ϕ_a > $\pm 8°$	RMS Roll Amplitude deg	Probability that ϕ_a > $\pm 5°$	Probability that ϕ_a > $\pm 8°$	Combined Probability that ϕ_a > $\pm 5°$	Combined Probability that ϕ_a > $\pm 8°$
3.2	0.01	0	0	0	0	0	0	0	0	0	0
8.4	0.09	3.71	0.40	0.10	0.04	0.01	2.86	0.22	0.02	0.02	0
11.0	0.22	5.12	0.62	0.30	0.14	0.07	3.79	0.42	0.11	0.09	0.02
13.6	0.29	4.88	0.59	0.26	0.17	0.08	3.62	0.39	0.09	0.11	0.03
16.2	0.21	4.15	0.48	0.16	0.10	0.03	3.09	0.27	0.04	0.06	0.01
18.8	0.11	3.43	0.35	0.07	0.04	0.01	2.57	0.15	0.01	0.02	0
21.4	0.05	2.83	0.21	0.02	0.01	0	2.13	0.06	0	0	0
24.0	0.01	2.36	0.11	0	0	0	1.78	0.02	0	0	0
Conditional Probability					Σ 0.50	Σ 0.19				Σ 0.30	Σ 0.06
Pierson-Moskowitz (T_o = 9.35 sec)		4.50	0.54	0.21	—	—	3.37	0.33	0.06	—	—
Bretschneider with Maximum Probability Modal Period (T_o = 10.8 sec)		5.10	0.62	0.29	—	—	3.77	0.42	0.11	—	—

TABLE 3 - HYDRODYNAMIC PERFORMANCE ASSESSMENT AT A SHIP SPEED OF 12 KNOTS IN SHORT CRESTED, WORST HEADING SEAS WITH $(\zeta_w)_{1/3}$ = 3.5 M (11.5 FT)

		Unstabilized					Fin* (Active) BK_2				
Modal Period, T_o sec	Frequency of Occurrence	RMS Roll Amplitude deg	Probability that $\phi_a >$ $\pm 5°$	Probability that $\phi_a >$ $\pm 8°$	Combined Probability that $\phi_a >$ $\pm 5°$	Combined Probability that $\phi_a >$ $\pm 8°$	RMS Roll Amplitude deg	Probability that $\phi_a >$ $\pm 5°$	Probability that $\phi_a >$ $\pm 8°$	Combined Probability that $\phi_a >$ $\pm 5°$	Combined Probability that $\phi_a >$ $\pm 8°$
3.2	0.01	0.03	0	0	0	0	0	0	0	0	0
8.4	0.09	6.05	0.71	0.42	0.07	0.04	3.77	0.42	0.11	0.04	0.01
11.0	0.22	4.86	0.59	0.26	0.13	0.06	2.57	0.15	0.01	0.03	0.00
13.6	0.29	3.89	0.44	0.12	0.13	0.04	1.70	0.01	0	0	0
16.2	0.21	3.08	0.27	0.03	0.06	0.01	0.96	0	0	0	0
18.8	0.11	2.47	0.13	0.01	0.01	0.00	0.47	0	0	0	0
21.4	0.05	2.01	0.05	0	0	0	0.11	0	0	0	0
24.0	0.01	1.65	0.01	0	0	0	0	0	0	0	0
Conditional Probability					Σ 0.40	Σ 0.14				Σ 0.08	Σ 0.01
Pierson-Moskowitz (T_o = 9.35 sec)		5.59	0.67	0.36	—	—	3.34	0.33	0.06	—	—
Bretschneider with Maximum Probability Modal Period (T_o = 10.8 sec)		4.94	0.60	0.27	—	—	2.65	0.17	0.01	—	—

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